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Quantifying Flux for (Bulk) Radiation Damage Studies

It is an experimental fact that the degradation of silicon devices caused by radiation damage to the bulk silicon (as opposed to those caused by surface or interface effects) is roughly proportional to the amount of displacement damage (creation of vacancies & interstitials), measured in terms of the total kinetic energy imparted to displaced silicon atoms[1]. Charged hadrons lose energy primarily by multiple Coulomb scattering, so bulk damage is usually expressed in terms of the damage that would be caused by a given flux of neutrons. Since the kinetic energy imparted to recoil silicon nuclei by incident neutrons depends strongly on the neutron energy, it is conventional to express bulk damage relative to the damage that would be caused by a given flux of 1 MeV neutrons. This is formalized by the American Society for Testing and Materials in E 772-94, “Standard Practice for Characterizing Neutron Energy Fluence Spectra in Terms of an Equivalent Monoenergetic Neutron Fluence for Radiation-Hardness Testing of Electronics.”

The observation that bulk damage is proportional to the total kinetic energy imparted to displaced silicon atoms is sometimes called “the NIEL hypothesis.” NIEL stands for “Non Ionizing Energy Loss,” and is expressed in units of *keVcm*^{2}*/gm*. The total Kinetic Energy Released in (silicon) MAtter is called “KERMA,” and it is calculated by multiplying the NIEL value by the incident fluence and by the weight in grams of the irradiated silicon sample:

$$KERMA(keV) = NIEL(keV\frac{cm^2}{gm}) \times \phi(\frac{\#}{cm^2}) \times wt(gm)$$

The same quantity is often given in terms of the “displacement damage cross section” D, expressed in units of *MeVmb*. To compute the total KERMA from D, one multiplies by the incident fluence and by the number of irradiated silicon atoms, remembering the definition of a barn:

$$KERMA(MeV) = D(MeVmb) \times \phi(\frac{\#}{cm^2}) \times (\#Si) \times (\frac{10^{-27}\ \mathrm{cm}^2}{\mathrm{mb}})$$

To confuse things, D is often called NIEL. The relationship between D and NIEL can be calculated, remembering Avogadro’s number (6.022 x 10^{23} atoms per mole) and the weight of one mole of silicon (A = 28.086 gm/mole). The conversion factor is:

$$100MeVmb = 2.144keV\frac{cm^2}{gm}$$

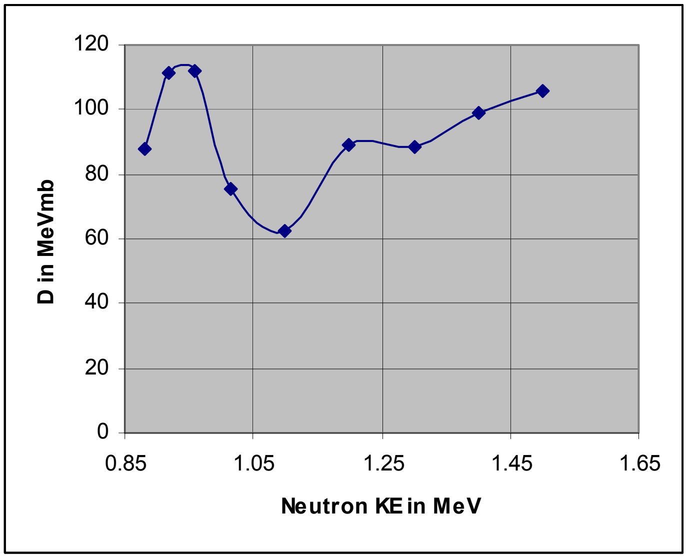
Here’s the arithmetic:

$$100MeVmb \times \frac{10^3 keV}{MeV} \times \frac{10^{-27} cm^2}{mb} \times (\frac{mole(Si)}{28.086gm}) \times (\frac{6.022 \times 10^{23}}{mole(Si)}) = 2.144keV\frac{cm^2}{gm}$$

It is an unfortunate fact that the displacement damage caused by neutrons of energy close to 1 MeV is a very strong function of energy (see below). As a result, the ASTM standard specifies

[1] A notable exception is the ROSE result on damage to oxygenated silicon sensors.

that a “[1 MeV] neutron displacement kerma factor” of 95 *MeVmb* shall be used when calculating the equivalent 1 MeV neutron fluence for an irradiation.



Neutron displacement damage as a function of energy, from E 722-94 (1998 Annual Book of ASTM Standards)

We have measured bulk radiation damage effects using the 200 MeV proton beam at the Indiana University Cyclotron Facility (IUCF). In order to express our results in terms of “equivalent 1 MeV neutrons,” we need the displacement damage cross section (or NIEL) for 200 MeV protons. I have found two values:

From Mika Huhtinen’s presentation at the CMS COTS Workshop (16-17 Nov. 1999) : 94 *MeVmb.* Presentation available at: http://www.physics.ohio-state.edu/~gilmore/cms/rad_test/tut2.pdf .

From Summers, et al., IEEE Trans. Nucl. Sci. Vol. 40, #6, pp 1372-1379 (Dec. 1993) “Damage Correlations in Semiconductors Exposed to Gamma, Electron, and Proton Radiations”:
1.940 $keVcm^2/gm$ = 90.5 *MeVmb.*

Therefore, the fluence of 200 MeV protons needs to be divided by a number no larger than 95/90.5 (1.05) to yield an equivalent fluence of 1 MeV neutrons.